TRI-BAND RAT-RACE COUPLER USING RESONATORS

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This paper presents a novel method to design a tri-band rat-race coupler by using resonators in π-shaped structure. The proposed structure demonstrates tri-band performance and a compact size due to π-shaped structure. In order to achieve tri-band operation, we use resonators and stubs with conventional rat-race coupler structure. By sharing the stub with resonator of two adjacent π-shaped circuits and making stubs inside the tri-band rat-race coupler, compactness is well kept. Compare to the size of 1 GHz conventional rat-race coupler, 84% reduction is archived by our proposed structure. We demonstrate that insertion losses are better than 4 dB, the reflection coefficients are better than 10 dB, and the isolations are better than 22 dB. In phase difference is less than 2.3°.

***Index Terms*—resonator, rat-race coupler, tri-band, π shaped structure.**

I. INTRODUCTION

Interoperability and co-existence between multi standards is the main critical issue in modern communication systems [1]. To satisfy this harsh requirement, multi-band or broadband radio systems are proposed to be used at different frequencies associated with different standards. To be used in multiband or broadband radio system, it is required to develop new type of multiband component such as power combiner, hybrid coupler and rat-race coupler. Also one of the requirements of developing the various microwave components is to reduce the size, complexity and cost [2]. Especially in this paper, we will present a novel type of multiband rat-race coupler.

Rat-race coupler is widely used in multi-standard microwave system. For example, in class-D switching-mode power amplifiers [3], and in the transmitter end of MIMO systems [4], it is widely used for dividing an input signal into two signals having 0^o and 180^o phase difference [5]. However, due to $\lambda/4$ transmission line, traditional design is limited at one single band [5]-[7]. Recently, the following researches are presented to realize multi-band operation of rat-race coupler. Dual-band quarter-wave composite right/left-handed transmission line (CRLH TL) is presented [5], and applied in rat-race coupler [4], [5], [8]. Stepped-impedance microstrip line is analyzed and used for dual-band operation [2], [6]. The C-section together with two transmission line sections is proposed and synthesized [1]. Size reduction is considered in design procedure [2], [4], [9].

In this paper, we present a novel compact tri-band rat-race coupler by using resonators and open stubs at both ends of $\lambda/4$ transmission line.

II. PROPOSED TRI-BAND TOPOLOGY

The conventional rat-race coupler is shown in Fig. 1.

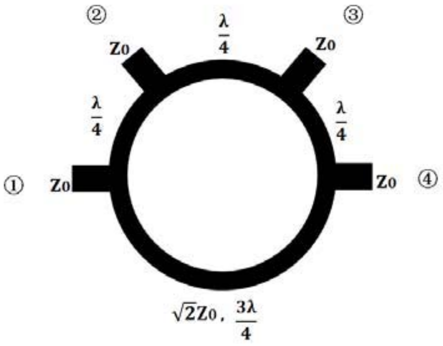

Fig. 1. Conventional rat-race coupler structure.

The proposed topology of tri-band rat-race coupler is shown in Fig. 2. The characteristic impedance is Z_0=50 Ω.

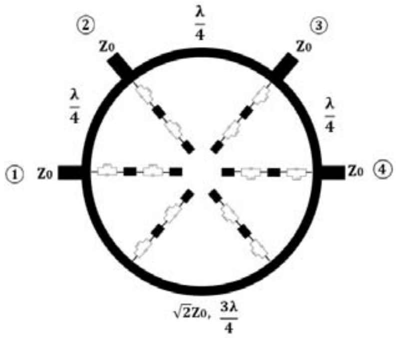

Fig. 2. The topology of the proposed tri-band rat-race coupler.

To make a tri-band rat-race coupler, the resonator is used in π -shaped structure as shown in Fig.3. Resonance is created by capacitor and inductor in parallel. The relationship is shown in (1).

$$f = \frac{1}{2\pi\sqrt{LC}} \qquad (1)$$

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Before analyzing the whole topology of tri-band rat-race coupler, we will explain π-shaped structure with resonators in Fig. 3.

The line l_1 is $\lambda/4$ length at frequency f_1 with the impedance of Z_1=70.7 Ω. At both ends of l_1, we put one stub with impedance Z_2 with length l_2 between resonator f_1 and resonator f_2. After resonator f_2, we add one open stub with impedance Z_2 and length l_3. Resonators f_1 and f_2 are specially designed to block the signal generated at frequency f_1 and f_2, respectively.

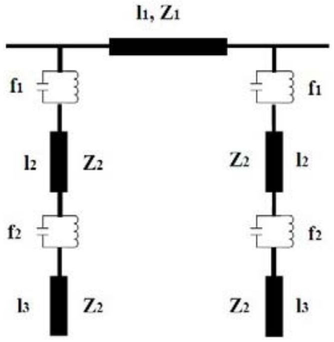

Fig. 3. The proposed π-shaped structure.

Fig. 4 shows the principle of π-shaped structure. At frequency f_1, the signal is blocked by the first resonator f_1 and the proposed π-shaped structure becomes a simple transmission line (Fig. 4(a)). At frequency f_2, the signal passes through resonator f_1 and be blocked by resonator f_2. Our proposed π-shaped structure transforms to a simple π-shaped circuit as shown in Fig. 4(b). Finally at frequency f_3, the first stub l_2 is added to the second stub l_3 to be considered as one longer open stub l_2+l_3 (Fig. 4(c)).

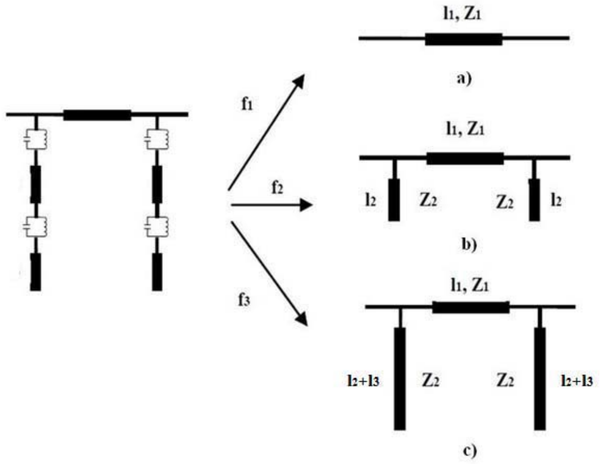

Fig. 4. Principle of tri-band operation.

In order to calculate the length l_2 and l_2+l_3 and impedance Z_2, we use ABCD matrix that allows simplifying the calculation.

At f_2, Fig. 4(b) with symmetrical structure at both ends of $l_1$corresponds to the following matrix [3]:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ jY_2 \tan\beta_2 l_2 & 1 \end{bmatrix} * \begin{bmatrix} \cos\beta_2 l_1 & jZ_1 \sin\beta_2 l_1 \\ jY_1 \sin\beta_2 l_1 & \cos\beta_2 l_1 \end{bmatrix} * \begin{bmatrix} 1 & 0 \\ jY_2 \tan\beta_2 l_2 & 1 \end{bmatrix} \tag{2}$$

Where $\beta_2 = \frac{2\pi}{\lambda_2}, l_1 = \frac{\lambda_1}{4}, Z_1 = 70.7\Omega.$

At frequency f_2, ABCD matrix of a quarter wavelength ($\lambda/4$) transmission line with impedance Z_{01} can be expressed as:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 0 & jZ_{01} \\ jY_{01} & 0 \end{bmatrix} \tag{3}$$

Similarly, at f_3, the matrix of Fig. 4(c) will be:

$$\begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ jY_2 \tan\beta_3 (l_2 + l_3) & 1 \end{bmatrix} * \begin{bmatrix} \cos\beta_3 l_1 & jZ_1 \sin\beta_3 l_1 \\ jY_1 \sin\beta_3 l_1 & \cos\beta_3 l_1 \end{bmatrix} * \begin{bmatrix} 1 & 0 \\ jY_2 \tan\beta_3 (l_2 + l_3) & 1 \end{bmatrix} \tag{4}$$

Where $\beta_3 = \frac{2\pi}{\lambda_3}, l_1 = \frac{\lambda_1}{4}, Z_1 = 70.7\Omega.$

The quarter wavelength transmission line with impedance Z_{02} at frequency f_3 can be expressed as:

$$\begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix} = \begin{bmatrix} 0 & jZ_{02} \\ jY_{02} & 0 \end{bmatrix} \tag{5}$$

Ideally the equivalent length of the proposed π-shaped circuit should be $\lambda_1/4$, $\lambda_2/4$ and $\lambda_3/4$ at frequency f_1, f_2, and f_3, respectively. To do that, we have to satisfy the condition of rat-race coupler for these three frequencies.

By equalizing the equations (2) and (3), we can deduce:

$$A = \cos\beta_2 l_1 - Y_2 Z_1 \tan\beta_2 l_2 \sin\beta_2 l_1 = 0$$
$$\Rightarrow Z_1 \tan\beta_2 l_1 = Z_2 \cot\beta_2 l_2 \tag{6}$$

$$B = jZ_1 \sin\beta_2 l_1 = jZ_{01}$$
$$\Rightarrow Z_{01} = Z_1 \sin\beta_2 l_1 \tag{7}$$

$$C = jY_2 \tan\beta_2 l_2 \cos\beta_2 l_1 + jY_1 \sin\beta_2 l_1 - jY_2 Y_2 Z_1 \tan\beta_2 l_2 * \tan\beta_2 l_2 \sin\beta_2 l_1 + jY_2 \tan\beta_2 l_2 \cos\beta_2 l_1 = jY_{01} \tag{8}$$

$$D = \cos\beta_2 l_1 - Y_2 Z_1 \tan\beta_2 l_2 \sin\beta_2 l_1 = 0$$
$$\Rightarrow Z_1 \tan\beta_2 l_1 = Z_2 \cot\beta_2 l_2 \tag{9}$$

Similarly for frequency f_3, we can deduce:

$$\Rightarrow Z_1 \tan \beta_3 l_1 = Z_2 \cot \beta_3 (l_2 + l_3) \qquad (10)$$

$$\Rightarrow Z_{02} = Z_1 \sin \beta_3 l_1 \qquad (11)$$

Where $\beta_2 = \dfrac{2\pi}{\lambda_2}, \beta_3 = \dfrac{2\pi}{\lambda_3}, l_1 = \dfrac{\lambda_1}{4}, Z_1 = 70.7\Omega.$

In equation (9), by giving Z_2=50Ω, we can calculate the stub length l_2. By (7), Z_{01} is obtained as 57.2Ω. With the same way using (10) we can find the value of l_2+l_3 and Z_{02} = 41.6Ω. The calculated Z_{01} and Z_{02} are far from the ideal value 70.7Ω. We have to increase the value of Z_1 in (7) and (11) to obtain the best performance of tri-band operation.

III. SIMULATED AND MEASURED RESULTS

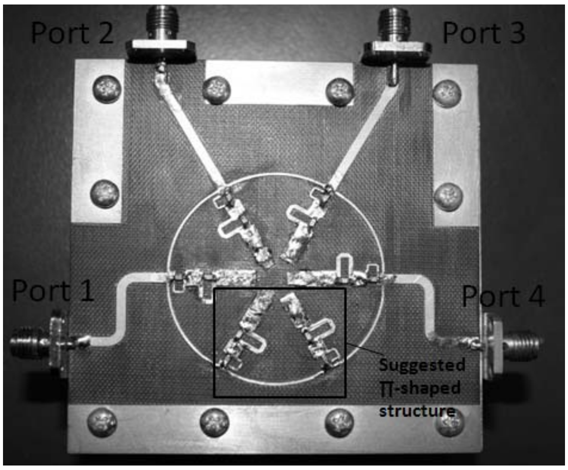

Fig. 5. Fabricated tri-band rat-race coupler.

We fabricate circuit by using the substrate Taconic TLX-8 with dielectric constant 2.55 at the frequencies 1GHz/1.5GHz/2.5GHz as shown in Fig. 5.

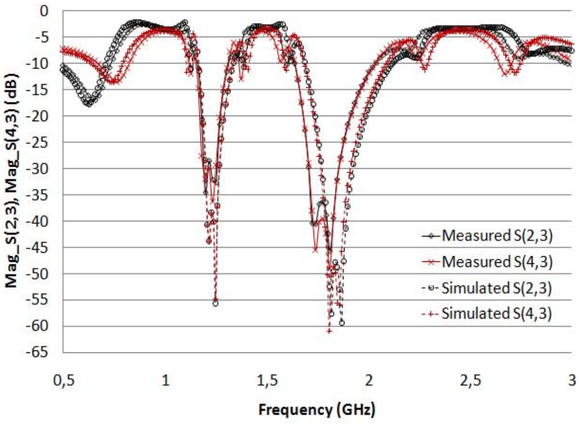

Fig. 6. Simulated and measured results of insertion loss of S_{23} and S_{43}.

By combining two adjacent π-shaped lines as one, the number of these lines added on initial rat-race coupler is reduced to six instead of twelve. Because our proposed structure is based on the conventional rat-race coupler for 2.5 GHz, the size of our coupler is 84% smaller than conventional rat-race coupler at 1 GHz. The measured and simulated results are compared in Fig. 6 to Fig. 12. For three frequencies, insertion losses are better than 4 dB. The reflection coefficients are better than 10 dB, and the isolation between port 1 and 3, port 2 and 4 are better than 26 dB and 22dB, respectively. In phase difference ∠S23-∠S43 is less than 2.3°. Out-of-phase difference ∠S21-∠S41 is less than 183.8°.

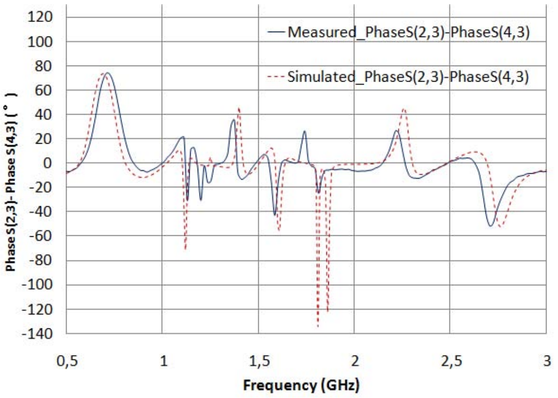

Fig. 7. Simulated and measured results of $\angle S_{23}$-$\angle S_{43}$.

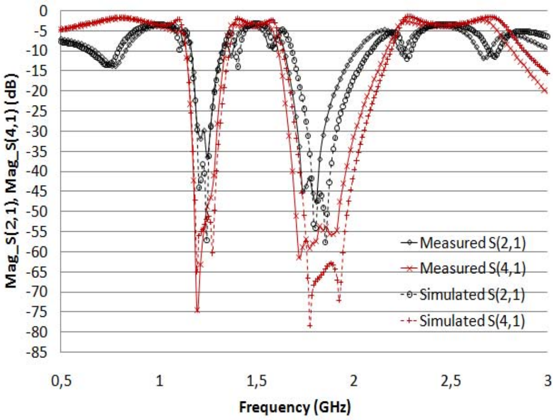

Fig. 8. Simulated and measured results of insertion loss of S_{21} and S_{41}.

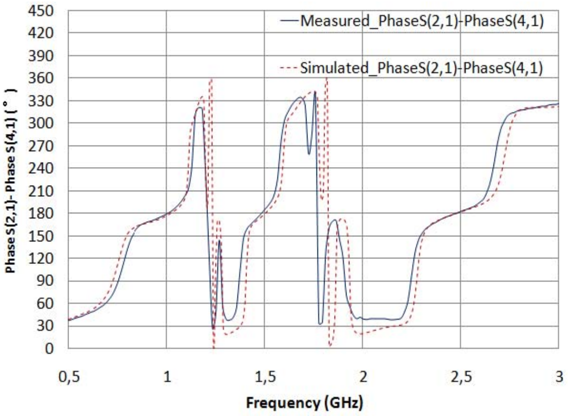

Fig. 9. Simulated and measured results of $\angle S_{21}$-$\angle S_{41}$.

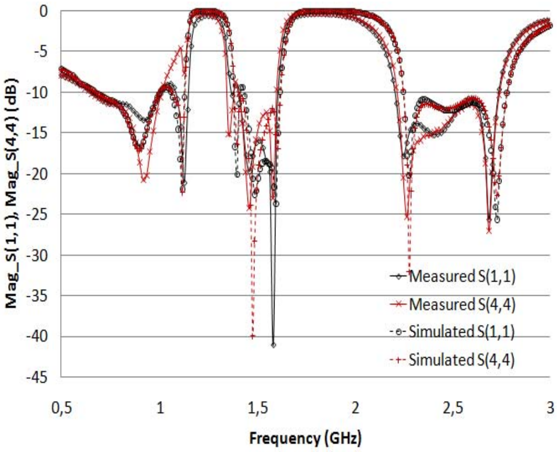

Fig. 10. Simulated and measured results of reflection coefficient of S_{11} and S_{44}.

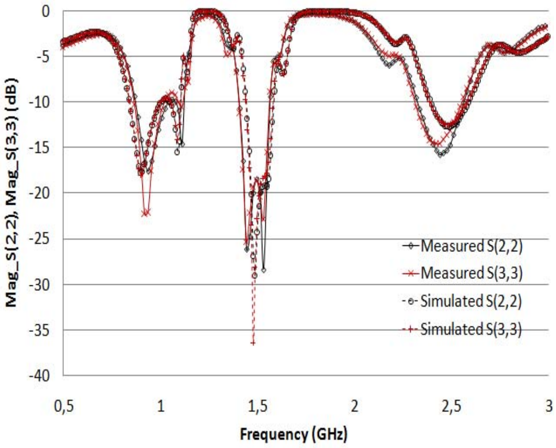

Fig. 11. Simulated and measured results of reflection coefficient of S_{22} and S_{33}.

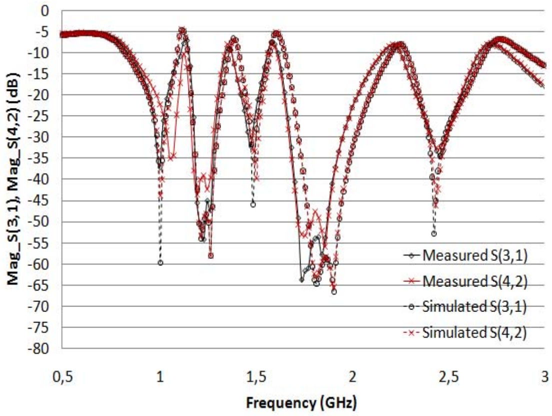

Fig. 12. Simulated and measured results of isolation of S_{31} and S_{42}.

IV. CONCLUSION

A simple and compact tri-band rat-race coupler at 1 GHz, 1.5 GHz and 2.5 GHz frequency has been presented in this paper. We use π-shaped structure which contains four resonators and microstrip lines. By using π-shaped circuits with resonators, one compact tri-band coupler is obtained. In addition, because we designed our tri-band coupler based on the highest frequency at 2.5 GHz, compare to 1GHz conventional rat-race coupler, the size of our tri-band rat-race coupler is 84% smaller. The measured result of our proposed rat-race coupler is comparable with the previous work for dual-band operation even though our coupler is working for tri-band application [6]. This methodology can be used further for multiband application.

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